Significance of Radiation Exposure From Work-Related Chest X-Rays for Epidemiological Studies of Radiation Workers

J. Cardarelli, PhD,[1]* H. Spitz, PhD,[1,2] C. Rice, PhD,[3] R. Buncher, ScD,[3] H. Elson, PhD,[4] and P. Succop, PhD[3]

Background *Previous epidemiologic studies of workers at nuclear weapons facilities have not included X-ray exposures as part of the occupational radiation exposure. The research objective was to determine the contribution of work-related chest X-ray (WRX) exposure relative to the cumulative occupational radiation exposure.*

Methods *Cases and controls were identified from a cohort of workers whose employment began as early as 1943. Medical records for 297 subjects were used to determine the bone marrow dose from their X-ray examinations. Individual dose data, however, were only available for 45 workers. Bone marrow dose estimates were calculated by converting the entrance-skin-exposure (from X-ray procedures) and occupational exposure (from monitoring data) to dose.*

Results *Stereoscopic photofluorography delivered a bone marrow dose nearly 100 times that delivered by today's chest X-ray technique. Photofluorography was the predominant radiation source during the 1940s and 1950s. The cumulative WRX dose was, on average, 50 times their occupational doses. No correlation between occupational and WRX dose was found, but may be due to the small study size and incomplete dose data.*

Conclusions *These findings illustrate the importance of including WRX doses in retrospective epidemiological studies of radiation workers, especially if photofluorographic chest X-rays were performed and occupational exposure to ionizing radiation is low.* Am. J. Ind. Med. 42:490–501, 2002. *Published 2002 Wiley-Liss, Inc.*[†]

KEY WORDS: *X-rays; medical surveillance; stereoscopic X-rays; photofluorography; bone marrow; radiation; occupational exposure; dose*

[1]National Institute for Occupational Safety & Health, Robert A Taft Laboratories (R-44), Health-Related Energy Research Branch, 4676 Columbia Parkway, Cincinnati, Ohio

[2]Department of Mechanical, Industrial, and Nuclear Engineering, University of Cincinnati, Cincinnati, Ohio

[3]Department of Environmental Health, University of,Cincinnati, Cincinnati, Ohio

[4]Barrett Cancer Center, University of Cincinnati, Cincinnati, Ohio

*Correspondence to: John Cardarelli, National Institute for Occupational Safety & Health, Robert A Taft Laboratories (R-11), Hazard Evaluation, Technical Assistance Branch 4676 Columbia Parkway, Cincinnati, Ohio 45226-1998. E-mail: jcardarelli@cdc.gov

INTRODUCTION

The majority of knowledge about risks to humans from radiation exposure has been derived from the study of highly exposed populations, such as the Japanese atomic bomb survivors, persons treated for disease using radiation, radium dial painters, and former uranium miners [NRC, 1990]. These risk estimates are the basis for protection standards, even though most lifetime exposures are much lower than those upon which the standards have been based. In fact, risk estimates for cumulative occupational exposure are based upon a linear extrapolation of the risks from higher cumulative exposures. This extrapolation method has been the subject for some recent controversy [NCRP, 2001].

The conventional exposure assessment strategy used in epidemiologic studies of radiation workers was to determine their exposures from existing occupational radiation exposure records. However, these records do not include information on the number and frequency of work-related X-ray examinations (WRX) received by workers because medically-related exposures were not considered an occupational exposure. Furthermore, guidance from technical advisory committees and government regulations specifically exempt facilities from including medically-related exposures [ICRP, 1977; NCRP, 1993; CFR, 2002]. In practice, workers were directed to remove their radiation dosimeter whenever X-ray examinations were performed so that the radiation exposure would not interfere with measurements of occupational exposure. On the other hand, historical health monitoring practices required that workers receive periodic chest X-rays as a condition of their employment, especially if their job placed them in a hazardous work environment [Cantril, 1946; Cantril et al., 1946].

The objective of this research is to determine the contribution of WRX exposure relative to the cumulative occupational radiation exposure received by workers at the Oak Ridge Gaseous Diffusion Plant (code named K-25), a facility recognized as having a low penetrating radiation exposure potential. Historical records at the K-25 plant were reviewed to ascertain the number and type of WRX performed. Bone marrow dose associated with each X-ray was calculated for a subset of workers included in a multiple myeloma case-control study. Cumulative occupational radiation doses recorded for these workers were also converted to bone marrow dose for comparison with WRX doses.

Historical Medical Surveillance Program

During the fall and winter of 1942–1943, an extensive medical safety program was developed for Manhattan Engineering District (MED) workers involved in secret operations at government facilities primarily in Oak Ridge, Tennessee, Los Alamos, New Mexico, and Hanford, Washington. One of the first issues to be addressed by the Medical Section was protecting workers from toxic radiation and dusts from uranium salts [Ahnfeldt et al., 1966]. Workers also had to pass a pre-employment physical exam that included a photofluorographic chest X-ray. Fluoroscopic studies were conducted on those whose chest X-rays were difficult to interpret. Results of all these tests, except the fluoroscopic evaluations, were recorded in the workers' medical files.

Periodic or ''interval'' medical exams were scheduled for all workers on a frequency that depended upon the job classification. Three reasons for these examinations were (1) to present any symptoms or problems which may have had an occupational origin, (2) to detect and follow the progression of any sign of change resulting from occupational exposures, and (3) to identify and correct any working conditions that may have caused deleterious symptoms [Cantril, 1946]. This practice continues today with only the frequency of examinations changing over time [Schilling, 1973; Rom et al., 1983; Stellman et al., 1998]. In the early 1940s, radiation workers were examined monthly. By the mid-1940s, the interval was increased to 7 or 8 weeks for those directly involved in the radiation work [Cantril, 1946]. Other workers were scheduled for examinations at 3- to 6-month intervals. Between the 1960s and 1970s, the frequency of routine health examinations was reduced to annual for radiation workers and discontinued for workers considered unexposed to ionizing radiation. By the 1980s, radiation workers were scheduled to receive medical examinations once every 5 years, although government inspection reports document that the K-25 plant medical surveillance program continued to conduct chest X-rays annually [Cardarelli, 2000]. Thus, radiation workers as a group are likely to have received more chest X-rays than other workers.

Review of Radiographs and Work Related Chest X-Rays

A review of the K-25 chest X-ray films found in the historical medical records revealed that the photofluorographic technique was used during the 1940s and 1950s and was later replaced by more conventional techniques for medical screening. Although an outdated technique relative to current technology, photofluorography had widespread use throughout the United States for tuberculosis screening in the 1930s and was state-of-the-art medical technology when work at the gaseous diffusion plant was started as part of the Manhattan Project.

Two X-ray machines were used at the site during the 1940s and 1950s: (1) a General Electric (GE) Model KX-10 Photoroentgen X-ray machine, used primarily for photofluorography of the chest and (2) a Westinghouse 200 MA X-ray machine, used with an adjustable table and fluoroscopic attachment to examine extremities, spine, hips, skull, shoulder, and other non-thoracic locations. The Westinghouse

machine was also capable of producing a conventional 14″ × 17″ chest X-ray but it primarily served as a back up to the GE X-ray machine [Cardarelli, 2000]. The GE machine was used with a lyselia grid to produce miniature 4″ × 5″ stereoscopic posterior–anterior (PA) chest X-rays [Cardarelli, 2000]. The ''stereoscopic'' technique produces two images of the chest (on 4″ × 10″ film) at slightly different angles resulting in a three-dimensional image of the chest when viewed through a stereoscope [Mason, 1944; Hemphill and Diercks, 1945].

The techniques used to produce PA chest X-rays with the Westinghouse and GE machines were very different. In a conventional chest X-ray, the X-ray beam passes through the chest and directly exposes the film to produce an image of the chest [Quinn, 1945]. In a photofluorographic chest X-ray, the X-ray beam passes through the chest, exposes a fluorescent screen producing an image of the chest, and then the fluorescent screen is photographed (Fig. 1) [Verstandig and Ainsworth, 1944]. The photofluorographic technique delivered a higher exposure to the subject since more exposure time was required to produce a fluorescent image. During the late 1950s, photofluorography was phased out at the Oak Ridge K-25 plant and replaced with the conventional chest X-ray technique used today. Between the late 1950s until the early 1970s, only the conventional PA chest X-ray technique was employed at the site for routine chest X-ray examinations, which substantially reduced the radiation exposure delivered to the subjects per chest X-ray exam. In 1962, a Westinghouse 300 mA machine was installed, replacing the

previous machines. Additional X-ray exposure was introduced in the early 1970s when the health-monitoring program added a lateral (LAT) chest view to the routine chest X-ray examination procedure [Cardarelli, 2000]. A new Westinghouse 500 mA X-ray unit was installed in 1987 to replace the 300 mA machine. Routine PA and LAT chest views were performed through the year 2000. Thus, it is essential to know the evolution of specific X-ray techniques and procedures that were used in routine health monitoring examinations to accurately estimate the contribution of WRX to the total dose received by a worker [Preston-Martin, 1995; Cardarelli, 2000].

Occupational Radiation Exposures

Personnel exposures to external ionizing radiation were determined from film badge and thermolumenscent dosimeters, which measured the penetrating gamma radiation emitted from various radioactive sources at the site (uranium decay products, calibration sources, and other radioactive contaminants). Measurement results from 1943 through 1985 were stored in a computerized database representing ∼30% (12,000/40,000 workers) of the total workforce that ever worked at the plant through 1985. This low percentage of monitored workers is an outcome of practices employed at the site, which included variable dosimeter exchange frequencies and a limited selection criteria for monitoring workers [Cardarelli, 2000]. Watkins et al. [1997] suggested
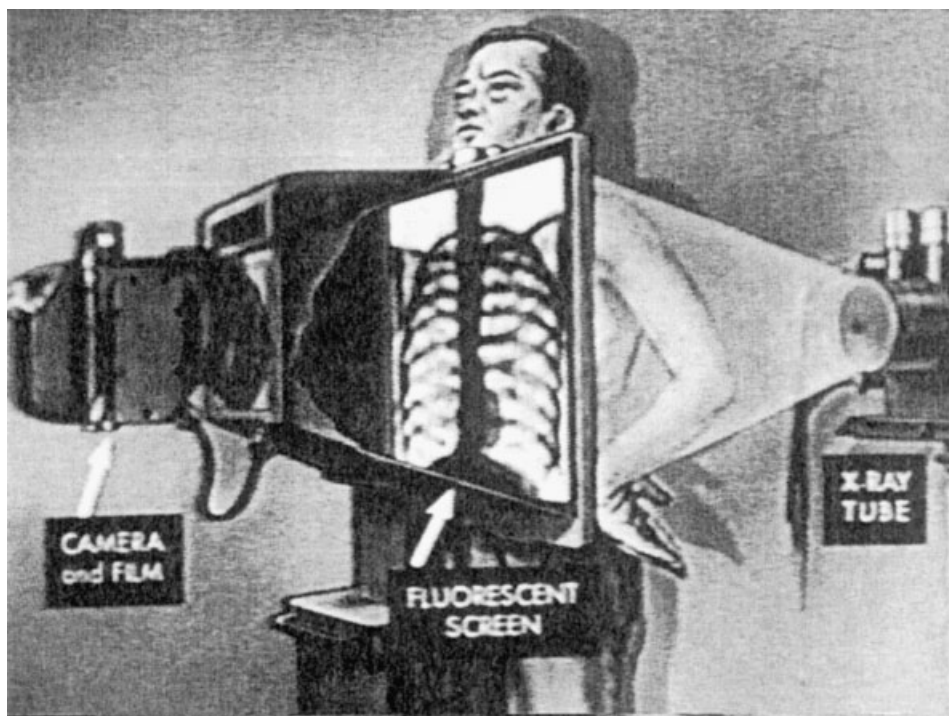

FIGURE 1. Photofluorographic technique used to obtain miniature 4″ × 5″ images of the chest; 1940s−1950s. Source: PHS [1946].

that unmonitored workers at K-25 were unexposed to radiation because site health physicists decided that few workers were at risk. However, review of the historical health physics administrative policies suggest that unmonitored workers could have received exposure but at levels below some regulatory threshold, and that monitored workers may have been monitored for only a fraction of their work history. Table I lists the descriptive statistics of the cumulative dosimetry results for these workers. Figure 2 illustrates the dose distribution for those workers ever monitored at the site between 1943 and 1985.

There were nearly 76,000 individual dosimeter results for 11,884 workers in the external dosimetry computer file. Approximately 70% of the doses in the file were recorded as zero and greater than 98% of the recorded cumulative doses for workers were less than 10 mSv (1 mSv = 100 mrem) [Galloway, 1992]. The large number of recorded zero doses suggests the use of an administrative practice to record zero doses below some threshold, usually the limit of detection. This practice was common at Department of Energy facilities [NIOSH, 1993; Watkins et al., 1997]. Although occupational radiation exposure data may be censored and incomplete, these limitations are similar to those routinely encountered in other epidemiological studies involving hazardous chemical or physical materials.

METHODS

Study Population

The overall study population consisted of workers that died from multiple myeloma (cases) and their respective controls selected from a cohort of 47,941 workers ever employed at the K-25 Gaseous Diffusion Plant. Five controls were selected for each case using an incidence density sampling strategy and matched on gender, race, and age-at-risk. A vital status update through 1989 found that 36% of this total work force was deceased [NIOSH, 1994]. A total of 364 potential study subjects (62 cases and 302 controls) were identified for the NIOSH study. Medical records for

TABLE I. Cumulative Occupational Dose for All Workers Ever Monitored at the Oak Ridge K-25 Plant: 1943–1985

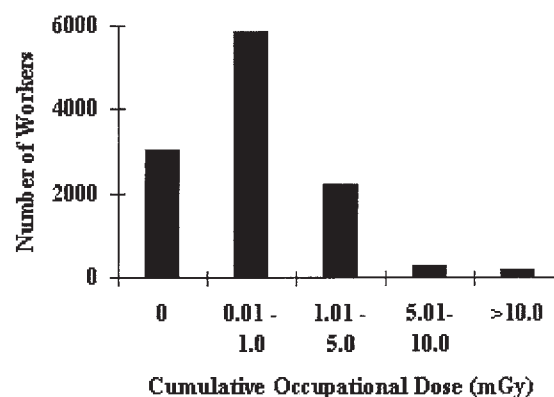| Parameter	Dose (mSv)[a]
Minimum dose	0
Maximum dose	89.2
Mean dose	3.1
Median dose	1.1
Geometric mean	0.5

N = 11,884.
[a] 1 mSv = 100 mrem.

FIGURE 2. Dose distribution of monitored workers at the K-25 gaseous diffusion plant 1943–1985 (N = 11,884).

297 workers (52 cases and 245 controls) were found in the on-site records vault; 58 workers (10 cases and 48 controls) were listed in the computerized external dosimetry database. For 45 workers (8 cases and 37 controls) medical records and computerized dosimetry data were available (Table II).

Statistical Analysis

The dosimetry records of the 297 workers with WRX data were used to describe exposures associated with the medical surveillance program at the facility. Records from 45 workers with both WRX and occupational exposures were used to assess exposure misclassification and to test the assumption that WRX exposures are randomly distributed among the working population. The latter was conducted using the PC/SAS statistical software package (PC/SAS Version 6.12, 1996).

Exposure Assessment From WRX Sources

Bone marrow dose was chosen as the metric for comparing exposures from WRX and occupational sources because (1) multiple myeloma originates in the bone marrow, (2) other researchers have used this metric to assess risk [Flodin et al., 1987; Yamamoto et al., 1988; Boice et al.,

TABLE II. Number of Study Subjects With WRX and Occupational External Dosimetry Results, Oak Ridge K-25 Plants

Study subjects	ALL subjects	WRX dose	Occupational dose[a]	Both
No. of cases	62	52	10	8
No. of non-cases	302	245	48	37
Total	364	297	58	45

[a] Numbers determined from search of computerized dosimetry file, N = 11,884.

TABLE III. Bone Marrow Dose Algorithm Parameter Values for Work-Related Chest X-Rays at the Oak Ridge K-25 Plant (1944–1999)

Time period	X-ray machine	Entrance skin exposure (Roentgen)			Bone marrow conversion factors (mGy/R)		Bone marrow dose (mGy)	
		PA	af[e]	LAT	PA	LAT	PA	LAT
1944–1956	GE model KX-10	2.488[a]	0.86	—	1.55	—	6.63	—
1944–1956	Westinghouse 200 mA	0.050[b]	0.14	—	1.55	—	0.01	—
1957–1961	Westinghouse 200 mA	0.050[b]	—	—	1.55	—	0.08	—
1962–1969	Westinghouse 300 mA	0.026[c]	—	—	1.55	—	0.04	—
1970–1986	Westinghouse 300 mA	0.010[d]	—	0.030[d]	1.55	0.66	0.01	0.02
1987–2000	Westinghouse 500 mA	0.022[d]	—	0.035[d]	1.55	0.66	0.03	0.02

[a]Quinn, 1945; Cardarelli, 2000.
[b]Rising and Soldat, 1959.
[c]Kereiakes and Rosenstein, 1980.
[d]Site specific calibration data.
[e]Adjustment factor is a percentage that represents the average frequency of photofluorography versus conventional X-ray examinations conducted during the specific time period.

1991; Kato et al., 1991; Gilbert et al., 1996; Kato et al., 2001], and (3) methods have been developed to calculate bone marrow dose from radiation exposures [Kereiakes and Rosenstein, 1980; ICRP, 1987; ICRU, 1988; Johansson et al., 1995]. The method of Kereiakes and Rosenstein [1980] used in this study converts WRX entrance-skin-exposures (ESE) into bone marrow dose. Values for ESE and bone marrow dose conversion factors listed on Table III show how the ESE changed with time according to the chest X-ray technique. The bone marrow dose conversion factors applied for chest PA and LAT X-rays were 1.55 mGy/R and 0.66 mGy/R, respectively. An adjustment factor, *af*, was incorporated into the algorithm that represented the percentage of photofluorographic versus conventional chest X-ray examinations performed during the 1940s and 1950s.

Chest X-ray ESEs were determined from site-specific X-ray calibration reports and values reported in the scientific literature. Although the bone marrow dose conversion factors were constant, ESEs were known to change with time due to improvements in the technology [Birnkrant and Henshaw, 1945; Kereiakes and Rosenstein, 1980; Cardarelli, 2000]. For example, faster film speeds and the introduction of intensifying screens significantly reduced the duration and intensity of the X-ray beam resulting in a reduction in ESE. For all non-chest X-ray examinations, a single set of ESE values were taken from tables published in Kereiakes and Rosenstein [1980] and applied to the bone marrow dose algorithms.

The relationship between bone marrow dose, D, and ESE for the WRX exposures received between 1944 and 1956 is given by Equation (1):

$$D = ESE \times af \times CF_{bm} \times \#views \qquad (1)$$

where *D* is the bone marrow dose (mGy), *ESE* is the entrance-skin-exposure (R) associated with the particular X-ray technique used at the time, *af* is the adjustment factor that represents the percentage of photofluorography versus conventional X-ray examinations, CF_{bm} is the ESE to bone marrow dose conversion factor suggested by Kereiakes and Rosenstein [1980] (mGy/R), and *#views* is the number of views taken during the procedure (two views for photofluorography and one view for conventional chest X-ray procedure). Frequently, radiologists request X-ray procedures to be repeated when the image is not suitable for a diagnosis. No information was contained in medical records regarding these retakes, so this additional source of exposure could not be evaluated.

Exposure Assessment From Occupational Sources

Computerized records of occupational radiation exposures contain shallow and deep dose estimates, where the shallow dose reflects exposure limited to the skin and the

deep dose designates exposure received by all tissue and organs located throughout the body cavity. The deep dose was converted to a bone marrow dose using conversion factors recommended by ICRP and ICRU [ICRP, 1987; ICRU, 1988] and is similar to the conversions methods used by Gilbert et al. [1996]. For this study, it was assumed that the average photon energy for uranium decay products was ~200 keV and that a worker was in a variable (i.e., rotational) orientation with respect to the source of radiation. A rotational orientation was adopted because it results in the most realistic estimate of bone marrow dose from occupational sources and is consistent with mobility of the worker during the performance of a job (Table IV).

RESULTS

A total of 2,188 X-rays were performed among the 297 workers. Chest X-rays were performed most frequently (78.6%), followed by extremities (12.3%), lumbar spine (2.3%), and skull (2.2%). X-ray examinations of the shoulder, cervical spine, ribs, hips, thoracic spine, abdomen, and pelvis accounted for the remaining 4.6 percent of the X-rays (Table V).

Results from reviewing radiographs of the 87 randomly selected workers indicate that the photofluorographic chest X-ray technique was exclusively used for workers who retired before 1956. No stereoscopic films ($4'' \times 10''$) dated after 1956 were found in these medical X-ray records.

Entrance-skin-exposures from photofluorographic PA chest X-rays were 50–250 times greater than conventional PA chest X-rays [Verstandig and Ainsworth, 1944; Quinn, 1945; Cardarelli, 2000]. Figure 3 illustrates the calculated bone marrow dose (milliGray per procedure) over time from photofluorographic and conventional PA chest X-rays. The time period with the highest average bone marrow dose from chest X-rays occurred between 1943 and 1956 due to the use of the GE Model KX-10 Photoroentgen X-ray machine. The bone marrow dose from this machine was ~3.85 mGy for each view resulting in a total bone marrow dose of 7.70 mGy per each stereoscopic PA chest X-ray procedure. The

TABLE IV. Ratio of Bone Marrow Dose to Deep Dose Equivalent[a]

Photon energy (keV)	Conversion factors		
	AP	Rotational	Isotropic
80	0.400	0.924	0.732
100	0.457	0.988	0.793
200	0.532	1.038	0.832
500	0.595	1.005	0.802
1,000	0.659	1.000	0.812
3,000	0.759	0.971	0.844

[a]Determined from Tables C.1 and 6 of ICRP Report 51 (1987).

TABLE V. Frequency of X-Ray Examinations Found in the Medical Records of 297 Study Subjects, Oak Ridge K-25 Plant

Type	Number of examinations	Percent
Chest	1,719	78.56
Extremities	269	12.30
Lumbar spine[a]	50	2.28
Skull[b]	48	2.19
Shoulder[c]	31	1.42
Cervical spine	20	0.91
Ribs[d]	13	0.59
Hips[e]	12	0.55
Thoracic spine[f]	11	0.51
Abdomen[g]	8	0.37
Pelvis	7	0.32
Total	2,188	100

[a]Lumbar spine examinations include lumbar spine (43), coccyx (1), sacral spine (1), and sacral-iliac region (5).
[b]Skull examinations include skull (26), mandible (4), nose (2), paranasal sinuses (7), sinuses (8), and right cheek (1).
[c]Shoulder examinations include shoulder (29), clavicle (1), and sterno-clavicular (1).
[d]Rib examinations include ribs (6), lower rib cage (1), left ribs (4), right ribs (1), and sternum (1).
[e]Hip examinations include hip (11) and ilium/hip joint (1).
[f]Thoracic spine examinations include thoracic spine (6), spine (2), and dorsal spine (3).
[g]Abdominal examinations include abdomen (6), and K.U.B. (2).

conventional chest X-ray technique used less frequently during the same time period would have delivered a bone marrow dose of about 0.08 mGy. In 1970, a lateral (LAT) view was added to the conventional PA chest X-ray examination slightly increasing the total bone marrow dose delivered during the health screening exam.

The collective bone marrow dose delivered to the 297 workers being studied was 7.1 Gy from WRX photofluorographic PA chest X-ray examinations as compared to 0.07 Gy from all other WRX conventional X-ray examinations (Table VI). The maximum individual cumulative bone marrow dose from occupational exposure was 0.02 Gy. The mean and geometric mean cumulative bone marrow doses (N = 58 workers) were 2.57 and 1.64 mGy, respectively (Table VII).

Cumulative bone marrow doses for the 45 study subjects with both WRX and occupational data were categorized into quintiles based on their cumulative bone marrow dose. In four of the five groups, WRX accounted for over 95% of the total bone marrow dose (Fig. 4). In the lowest cumulative dose group, WRX accounted for nearly 70% of the dose. Seventy-eight percent (35/45) of the workers changed exposure category when WRX were considered, although this was not unexpected for a skewed distribution. Thirty-six percent (16/45) moved two or more exposure categories (Table VIII).
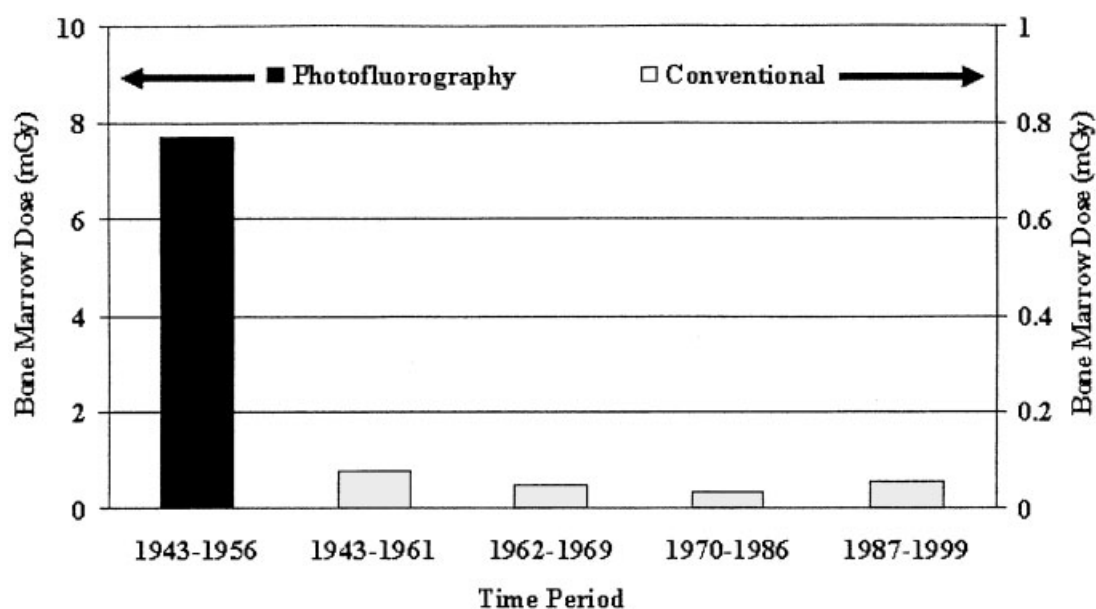
FIGURE 3. Bone marrow dose estimates for chest X-ray examinations, by time period and type.

Bone marrow doses from WRX exposures exceeded those from occupational exposures by nearly a factor of 50, on average (Table IX; N = 45). This finding was almost entirely due to the photofluorographic chest X-rays conducted during the 1940s and 1950s (Table VI).

Site specific historical documents suggest that workers assigned to potentially hazardous jobs were scheduled for health examinations at a greater frequency than workers considered "non-exposed" [Cardarelli, 2000]. Despite this suggestion, no statistically significant correlation between occupational and WRX dose was found among the 45 work-ers in this analysis (r = −0.007 Pearson, P = 0.96; r = 0.198 Spearman, P = 0.19).

DISCUSSION

Previous epidemiologic studies of workers employed at nuclear weapons facilities during the Manhattan project and subsequent Cold War typically do not include WRX as a source of occupational radiation exposure for several reasons. First, historical radiation monitoring records do not include WRX exposure estimates. Second, there is a perception

TABLE VI. Bone Marrow Dose Estimates for Work Related X-Rays Performed on 297 Oak Ridge K-25 Subjects[a]

Time period	Number of study subjects employed	Number of X-ray procedures	Chest film size (inches)	Cumulative bone marrow dose	
				Chest view (mGy)	Other views (mGy)
1943–1949	200	673	4 × 10	4,238.5	
		109	14 × 17	6.9	17.2
1950–1959	90	675	4 × 10	2,812.4	
		114	14 × 17	17.2	32.2
1960–1969	62	366	14 × 17	16.4	13.1
1970–1979	31	191	14 × 17	9.5	2.9
1980–1989	14	50	14 × 17	2.3	0.07
1990–1993	1	10	14 × 17	0.2	0.9
Total		2,188		7,103.4	66.3
Photofluorographic procedures		1,348		7,050.9	
Conventional procedures		840		52.5	66.3

[a]Any change over time is due to the study subjects work histories and does not reflect the workload of the medical X-ray department.

TABLE VII. Bone Marrow Dose Estimates Calculated From Whole Body Occupational Exposure Measured for 58 Radiation Workers[a]

Statistic	Bone marrow dose (mGy)
Minimum	0
Maximum	23.2
Mean	2.6
Median	1.2
Geometric mean	1.6

[a]Only 45 workers had WRX and occupational data.

among researchers that the contribution from chest X-rays is very low compared to other sources of radiation encountered at the workplace [Norwood et al., 1972]. Third, epidemiologists have traditionally assumed that exposure from WRX was randomly distributed throughout the working population, so that effects associated with this exposure would not influence the analysis [Gilbert, 1991; Mitchell et al., 1997]. And fourth, the effort necessary to retrieve, interpret, and evaluate this source of radiation exposure is large and costly. Studies that have evaluated X-rays used the number of X-rays received by a study subject or their duration of employment as a surrogate for exposure; none incorporated the radiation dose into their analyses [Cuzick and De Stavola, 1988; Boffetta et al., 1989; Davis et al., 1989; Wing et al., 1991; Eriksson, 1993; Hatcher et al., 2001].

In this exposure assessment study, WRX was included as part of the cumulative occupational dose estimate by combining the bone marrow dose contributions from WRX and occupational exposures. Combining WRX and occupational dose increased the number of workers with cumulative doses above 50 mGy (Table VIII), which has been shown to drive dose response relationships [Frome et al., 1997]. These results will be used in an ongoing NIOSH study to assess any relationship between multiple myeloma deaths among K-25 workers and several exposure parameters such as external ionizing radiation, chemicals, and uranium. WRX is considered as an additional source of external radiation [NIOSH, 1994]. The NIOSH study will complement the study by Wing et al. [2000] which combined the workers at four other DOE facilities (Los Alamos National Laboratory [LANL], Oak Ridge National Laboratory [ORNL], Savannah River Site, and Hanford) and reported a relationship between multiple myeloma deaths and exposure to *external penetrating ionizing radiation*. Wing et al. concluded that multiple myeloma was associated with low-level, whole body radiation doses at older ages, but that the cumulative dose was not associated with the disease. Although Wing et al. included the number of X-rays received by workers in their analyses, they did not assess the associated dose. These combined dose estimates may be especially important for evaluating health outcomes for workers at a low dose facility like the K-25 plant.

Gilbert [1991], Gilbert and Fix [1995] stated that dose from medical exposures is not likely to bias dose–response
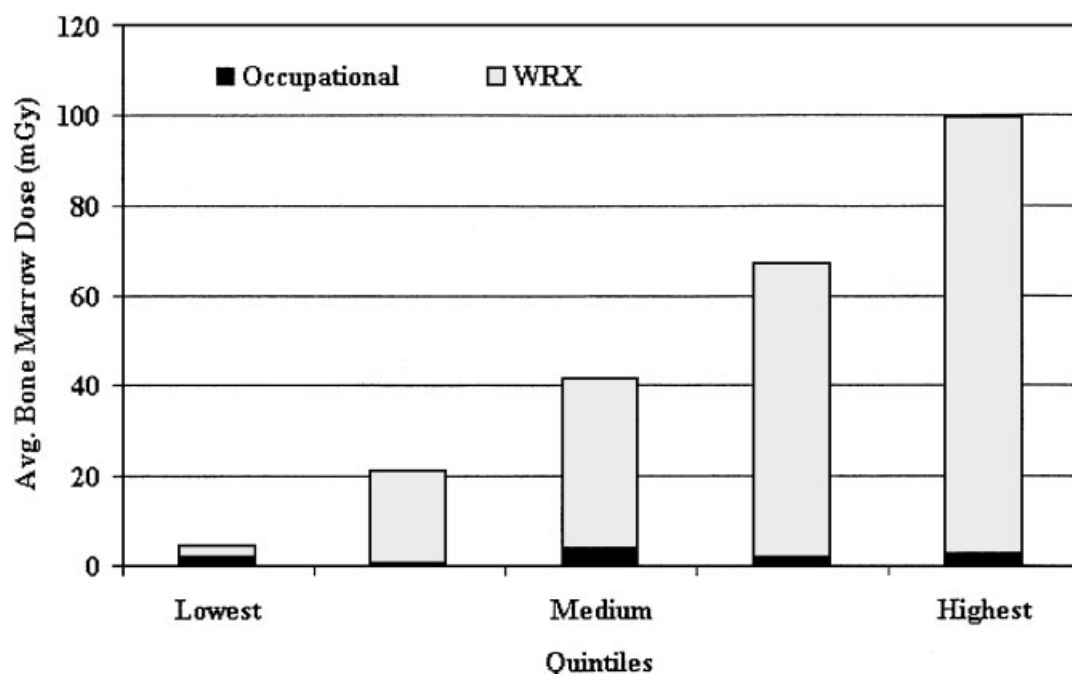

FIGURE 4. Average cumulative bone marrow dose from WRX and occupational exposures. Each quintile contains estimates for nine workers.

TABLE VIII. Changes Among Dose Categories Between Occupational and Total Dose Estimates (Occupational Plus WRX Dose)[a]

	Occupational + WRX doses (mGy)[a]				
76.8−< 131.7		*4*	*1*	*2*	**2**
50.2−< 76.8	*1*	*1*	*1*	**3**	*3*
29.5−< 50.2	*1*	*2*	**2**	*3*	*1*
13.4−< 29.5	*6*	**1**	*1*		*1*
0−< 13.4	**2**	*1*	*3*	*1*	*2*
Dose	0	0−< 0.9	0.9−< 1.3	1.3−< 2.0	2.0−< 24.0
Categories	Occupational doses only (mGy)[b]				

[a]Each category contains nine study subjects. Bold cells represent no change in worker categorization. Italic cells represent a change in worker categorization.

[b]Dose categories are a result from the desire to have an equal number of workers per quintile.

relationships unless the medical dose is strongly correlated with the occupational dose, and that no reason is known for suspecting a correlation. Although we collected site-specific reports that suggest medical dose is correlated with occupational dose, this study did not find a statistically significant correlation between WRX and occupational doses [Cardarelli, 2000]. However, the lack of a statistical correlation may be due to the small number of workers included in the analysis (N = 45) and the limited amount of occupational dose information. Further, risk coefficients could be biased even if WRX dose is uncorrelated with occupational dose, especially in the extreme situation as portrayed in this paper. Research on a larger group of workers is needed to better understand the strength of any correlation between WRX and occupational doses. It is possible in this limited exposure assessment that the dose estimates for the 45 subjects may be among the highest at the facility, since the selection criteria required both WRX and badge data. Because of the monitoring practices at this facility, workers having both WRX and badge data may have received greater exposure than non-monitored workers. A larger study would include workers with WRX only who had badge data either missing or set at zero. Nonetheless, the relationship between WRX and occupational dose could be different in other cohorts, especially during calendar periods before and after the use of photofluorographic technology.

Presently, there is no requirement for a standardized or centralized system that records WRX or other medical radiation exposures, although such a recommendation was made by Morgan [1974]. As a result, culling information on WRX exposures from the medical records for an epidemiologic study can be very resource intensive. Access to these records is not always available to non-government researchers which may also explain why WRX exposures have not been evaluated in past studies. However, even though NIOSH was granted access to the historical files, medical records for 19% (67/364) of the study subjects could not be found.

The method used to convert WRX exposures into bone marrow doses accommodates all the changes in X-ray techniques through time at the K-25 plant, including the use of photofluorographic X-rays. Further research is needed to determine if imputation strategies could be used to estimate WRX and occupational doses for workers with un-located or missing medical or dosimetry records. One method to estimate WRX doses from missing medical records would be to use the correlation between medical examinations and occupational exposure. Cantril [1946] stated that workers exposed to radiation and other hazardous chemicals had more frequent medical examinations (including routine chest X-rays), than "non-exposed" workers. Other sources of dose that impact estimates of WRX exposure are (1) the number of "retakes" examinations (ranging between 1 and 15% of the total number of exams), and (2) the undocumented exposure times (i.e., exposure intensity) for fluoroscopy examinations [Brandt et al., 1987; Boice et al., 1991; ICRP, 1993]. Retakes are repeated diagnostic X-rays that are required because initial films were of poor quality or improperly developed. Similarly, various methods have been developed to estimate the "missed dose" from occupational exposures for epidemiologic studies [NIOSH, 1993; Frome et al., 1997; Mitchell et al., 1997; Watkins et al., 1997]. Our research findings regarding WRX exposures indicate that it may be a major contributor to such "missing dose," especially if photofluorographic chest X-rays were used in a particular cohort.

The importance of diagnostic and therapeutic X-ray exposure and its relationship to various health outcomes has also been evaluated for atomic bomb survivors studied by the Radiation Effects Research Foundation (RERF) [Antoku et al., 1972; Russell and Antoku, 1976; Yamamoto et al., 1988; Kato et al., 1991; Kato et al., 2001]. Regular biennial clinical examinations of survivors in the RERF Adult Health Study (AHS) began in 1958. The examination schedule was set so that a representative cross section of the entire

TABLE IX. Bone Marrow Dose Estimates for 45 Study Subjects From WRX and Occupational Sources

| Subject Id | Cumulative bone marrow dose estimates (mGy)[a] | | | Duration of employment (years) | Year first employed |
	Work related X-ray dose	Occupational dose	Cumulative dose		
1	0.2	0.01	0.21	4.71	1979
2	0.3	5.3	5.6	3.66	1973
3	0.5	1.2	1.7	7.82	1973
4	1.0	6.4	7.4	37.67	1945
5	1.1	0.9	2.0	18.67	1973
6	1.7	1.3	3.0	10.69	1960
7	1.9	0.3	2.2	13.55	1973
8	2.3	1.1	3.4	19.11	1962
9	13.4	0.01	13.41	3.54	1953
10	13.7	0.4	14.1	9.27	1952
11	13.8	0.01	13.81	20.22	1945
12	14.3	0.01	14.31	4.89	1956
13	20.7	1.2	21.9	32.08	1949
14	21.0	0.01	21.01	2.15	1955
15	21.0	0.01	21.01	5.99	1952
16	26.6	0.01	26.61	2.13	1953
17	26.9	22.4	49.3	6.91	1953
18	27.2	1.1	28.3	31.86	1952
19	27.5	1.9	29.4	22.53	1950
20	33.2	0.01	33.21	3.82	1945
21	33.5	0.7	34.2	11.04	1951
22	33.8	1.3	35.1	25.01	1952
23	34.4	1.1	35.5	32.19	1950
24	39.9	1.2	41.1	6.14	1952
25	46.8	1.9	48.7	10.69	1951
26	47.2	1.8	49.0	34.43	1945
27	47.5	0.3	47.8	33.80	1944
28	54.1	1.8	55.9	33.79	1945
29	60.7	1.3	62.0	25.86	1944
30	60.9	0.01	60.91	24.44	1944
31	61.8	2.6	64.4	38.93	1945
32	63.1	0.5	63.6	35.69	1945
33	69.0	9.3	78.3	25.82	1945
34	70.0	1.4	71.4	36.94	1945
35	70.2	3.4	73.6	19.66	1944
36	73.4	3.3	76.7	13.43	1945
37	74.2	1.2	75.4	36.33	1945
38	80.8	1.2	82.0	34.92	1945
39	83.5	0.01	83.51	28.53	1944
40	89.3	0.6	89.9	30.97	1945
41	89.4	7.4	96.4	18.95	1945
42	95.0	0.2	95.2	19.41	1945
43	108.9	1.4	110.3	28.46	1944
44	127.3	0.3	127.6	18.44	1944
45	130.4	1.3	131.7	12.02	1945

[a]0.01 mGy was added to all dose estimates to facilitate log transformation.

population could visit the clinic during any month. Approximately 1.4% of the survivors have also received large therapeutic radiation doses [Kato et al., 2001] whereas the majority of survivors in the AHS were subject to biennial examinations that included routine abdominal and chest radiography [Kato et al., 1991]. It is unknown whether the photofluorographic technique was used by the RERF in performing chest X-ray examinations. These studies investigated excess mortality among survivors due to leukemia and cancers of the lung, breast, stomach, colon, and thyroid and salivary glands. Diagnostic and therapeutic medical X-ray doses were noted as a substantial contributor to the cumulative dose estimate and the authors concluded that medical X-rays doses should be included in the epidemiologic analyses, especially among the lowest exposed survivors.

This study demonstrates that WRX exposures, received as part of a work-related medical surveillance program, can be a significant contributor to cumulative radiation dose. Incorporating these types of exposures into the cumulative dose estimate may improve our understanding of the health affects associated with chronic low-level exposures to ionizing radiation. For example, Wing et al. [1991] concluded that the radiation-cancer dose response was 10 times higher for workers at ORNL than estimates from the follow-up of atomic bomb survivors. Two reasons provided by Wing et al. [1991] to possibly explain these controversial findings were concomitant chemical carcinogen exposures and an underestimate of cumulative dose in ORNL workers. WRX exposures were not mentioned in Wing et al. [1991] as a potential contributor to dose. Had such exposures been included in the cumulative dose estimates, the risks per unit dose may have been lower. However, further research is needed to assess the impact it may have on studies of larger worker populations, especially where the occupational exposures are higher with better monitoring data.

REFERENCES

Ahnfeldt A, Allen K, McFetridge E, Stein M, editors. 1966. Radiology in World War II. Washington DC: Office of the Surgeon General, Department of the Army. pp 841–844.

Antoku S, Russell WJ, Milton RC, Yoshinga H, Takeshita K, Sawada S. 1972. Dose to patients from roentgenography. Health Phys 23:291–299.

Birnkrant ML, Henshaw PS. 1945. Further problems in X-ray protection. I. Radiation hazards in photofluorography. Am Journal Radiography 44:565–568.

Boffetta P, Stellman SD, Garfinkel L. 1989. A case-control study of multiply myeloma nested in the American Cancer Society prospective study. Int J Cancer 43:554–559.

Boice JD, Morin MM, Glass AG, Friedman GD, Stovall M, Hoover RN, Fraumeni JF. 1991. Diagnostic X-ray procedures and risk of leukemia, lymphoma, and multiple myeloma. JAMA 265(10):1290–1294.

Brandt GA, Preub HJ, Leinweber P. 1987. Analysis of retakes in X-ray diagnosis. Radiol Diagn (Berl) 28:271–277 (In German).

Cantril S. 1946. Industrial Medical Program: Hanford Engineer Works. U.S. Atomic Energy Commission Technical Information Division, Oak Ridge Directed Operations, Oak Ridge, Tennessee. MDDC-602.

Cantril ST, Nickson JJ, Wirth JE, Stone RS. 1946. Requirements of an adequate health service in relation to atomic research and industrial development University of Chicago: Metallurgical Laboratory. MDDC-686.

Cardarelli J II. 2000. A potential consequence of excluding work-related X-ray exposures when computing cumulative occupational radiation dose at a uranium enrichment plant [dissertation]. Cincinnati (OH): University of Cincinnati.

CFR. Code of Federal Regulations. 2002. 10 CFR 20. Standards for protection against radiation. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

Cuzick J, De Stavola B. 1988. Multiple myeloma—A case-control study. Br J Cancer 57:516–520.

Davis FG, Boice JD, Hrubec Z, Monson RR. 1989. Cancer mortality in a radiation-exposed cohort of Massachusetts tuberculosis patients. Cancer Res 49:6130–6136.

Eriksson M. 1993. Rheumatoid arthritis as a risk factor for multiple myeloma: A case-control study. Eur J Cancer 29A:259–263.

Flodin U, Fredriksson M, Persson B. 1987. Multiple myeloma and engine exhausts, fresh wood, and creosote: A case-referent study. Am J Ind Med 12:519–529.

Frome EL, Cragle DL, Watkins JP, Wing S, Shy CM, Tankersley WG, West CM. 1997. A mortality study of employees of the nuclear industry in Oak Ridge, Tennessee. Radiat Res 148:64–80.

Galloway GR. 1992. Characterization and assessment of Oak Ridge gaseous diffusion plant dosimetry data for Oak Ridge associated universities health and mortality study of Department of Energy radiation workers [Thesis]. Chapel Hill, NC: University of North Carolina, Department of Environmental Sciences and Engineering.

Gilbert E. 1991. Studies of workers exposed to low doses of external radiation. Occupational Medicine: State Art Rev 6(4):665–679.

Gilbert E, Fix JJ. 1995. Accounting for bias in dose estimates in analyses of data from nuclear worker mortality studies. Health Phys 68(5):650–660.

Gilbert E, Fix JJ, Baumgartner WV. 1996. An approach to evaluating bias and uncertainty in estimates of external dose obtained from personal dosimeters. Health Phys 70(3):336–345.

Hatcher JL, Baris D, Olshan AF, Inskip PD, Savitz DA, Swanson GM, Pottem LM, Greenberg RS, Schwartz AG, Schoenberg JB, Brown LM. 2001. Diagnostic radiation and the risk of multiple myeloma (United States). Cancer Causes Control 12(8):755–761.

Hemphill SP, Diercks MW. 1945. Simple method for taking stereoscopic chest films. U.S. Nav M Bull 44:166–169.

ICRP. 1977. Recommendations of the International Commission on Radiological Protection. New York: Pergamon Press.

ICRP. 1987. Data for use in protection against external radiation. New York: Pergamon Press. ICRP Publication 51.

ICRP. 1993. Summary of the current ICRP principles for protection of the patient in diagnostic radiology. New York: Pergamon Press.

ICRU. 1988. Determination of dose equivalents from external radiation sources—Part 2. Bethesda, MD: ICRU Report No. 43.

Johansson L, Larsson L, Damber L. 1995. A cohort study with regard to the risk of haematological malignancies in patients treated with X-rays for benign lesions in the locomotor system: II. Estimation of absorbed dose in the red bone marrow. Acta Oncol 34(6):721–726.

Kato K, Antoku S, Sawada S, Russell WJ. 1991. Organ doses received by atomic bomb survivors during radiological examinations at the Radiation Effects Research Foundation. Br J Radiol 64:720–727.

Kato K, Antoku S, Kodama K, Kawamura S, Fujita Y, Komastu K, Awa A. 2001. Organ doses from radiation therapy in atomic bomb survivors. Radiat Res 155:785–795.

Kereiakes JG, Rosenstein M. 1980. Handbook of radiation doses in nuclear medicine and diagnostic X-ray. Ann Arbor, MI: CRC Press. pp 155–243.

Mason MW. 1944. Photofluorography for chest surveys. Radiology 43: 499–503.

Mitchell TJ, Ostrouchov G, Frome EL, Kerr GD. 1997. A method for estimating occupational radiation dose to individuals using weekly dosimetry data. Radiat Res 147:195–207.

Morgan KZ. 1974. Reducing medical exposure to ionizing radiation. Am Ind Hyg Assoc J 35:358–368.

NCRP. 1993. Limitation of Exposure to Ionizing Radiation Report Number 116. Bethesda, MD. p 47.

NCRP. 2001. Evaluation of the linear-nonthreshold dose-response model for ionizing radiation. Report Number 136. Bethesda, MD.

NIOSH. 1993. NIOSH Research Issues Workshop: Epidemiologic use of nondetectable values in radiation exposure measurements. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention. NTIS PB95-189601.

NIOSH. 1994. Protocol: Study of multiple myeloma among workers at the Oak Ridge Gaseous Diffusion Plant (K-25). Health-Related Energy Research Branch, Division of Surveillance, Hazard Evaluations, and Field Studies. Health-Related Energy Research Branch, Division of Surveillance, Hazard Evaluations, and Field Studies. Cincinnati, OH.

Norwood WD, Rising FL, Kirklin CW, Brodsky A, Sanders BS, Mancuso TF. 1972. Cumulative dose from Diagnostic Irradiation. Am J Roentgenol Radium Ther Nucl Med CXV(3):644–648.

NRC. 1990. Biological effects of ionizing radiation. Health effects of exposure to low levels of ionizing radiation (BEIR V). Washington, DC: National Academy Press.

PHS. 1946. "Techniques of Group Chest X-ray Services." Federal Security Agency, Division of Visual Education, U.S. Office of Education, Sun Dial Films, Inc., 1946.

Preston-Martin S. 1995. Dr. Preston-Martin Comments. Am J Epidemiol 141(9):884.

Quinn B. 1945. Mass miniature radiography of the chest using 4×5 in film. Radiography XI(125):33–37.

Rom WN, Renzetti AD, Lee JS, Archer VE, editors. 1983. Environmental and occupational medicine. 1st ed. Boston: Little, Brown and Company. pp 944–949.

Russell WJ, Antoku SA. 1976. Radiation therapy among A-bomb survivors. AJPH 66(8):773–777.

Schilling RSF, editor. 1973. Occupational health practice. London: Butterworths & Co. pp 67, 100–102, 415–416.

Stellman JM, McCann M, Warshaw L, Brabant C, Finklea J, Coppée GH, Hunt VR, Kraus RS, Laurig W, Messite J, Sauter SL, Spiegel J, Soskolne CL, Terracini B, Myers ML, Dufresne C, editors. 1998. Encyclopedia of occupational health and safety. 4th ed. Geneva: International Labour Office. pp 16.7–16.8.

Verstandig CC, Ainsworth CW. 1944. Photoroentgenographic technique and dark room procedure used at the army recruiting and induction station, New Haven, Connecticut. Am J Roentgenol 52:547–550.

Watkins JP, Cragle DL, Frome EL, Reagan JL, West CM, Crawford-Brown D, Tankersley WG. 1997. Collection, validation, and treatment of data for a mortality study of nuclear industry workers. Appl Occup Environ Hyg 12(3):195–205.

Wing S, Shy CM, Wood JL, Wolf S, Cragle DL, Frome EL. 1991. Mortality among workers at Oak Ridge National Laboratory: Evidence of radiation effects in follow-up through 1984. JAMA 265:1397–1402.

Wing S, Richardson D, Wolf S, Mihlan G, Crawford-Brown D, Wood J. 2000. A case control study of multiple myeloma at four nuclear facilities. Ann Epidemiol 10(3):144–153.

Yamamoto O, Antoku S, Russell WJ, Fujita S, Sawada S. 1988. Medical X-ray exposure doses as contaminants of atomic bomb doses. Health Phys 54(3):257–269.